A SPIN-DETECTION MAGNETIC MEMORY

The present invention relates to spin-detection magnetic memories.

Magnetic memories on silicon, also known as magnetic random access memory (MRAM) have been the subject of very rapid development over the last few years, and reference can be made on this topic to US patent No. 5 650 958, for example. They present numerous advantages, such as the non-volatility of "FLASH" memory, the speed of static memory (SRAM), and the density of dynamic memory (DRAM). In addition to these numerous advantages, they are also capable of operating at very low voltage.

Nevertheless, the method of fabricating MRAMs is complex. Very accurate control is required over certain parameters, as is the use of materials that are not easily available. Those memories are thus difficult to industrialize in profitable manner, and until now only a few prototypes have been produced.

A first type of spin transistor, such as that described in US patent No. 5 654 566 appears like a field-effect transistor (FET) except that its source and its drain are replaced respectively by an injector and a detector of spin-polarized electrons, both being made of magnetized magnetic material.

Spin-polarized electrons are injected from the injector into the channel of the transistor. They drift under the effect of the magnetic field applied between the injector and the detector. The grid serves to manipulate spin (change spin orientation) on the path from the injector to the detector.

The electric potentials of the three elements, i.e. the injector, the grid, and the detector, are conditioned by the operation of the transistor, such that it is not possible to modify them freely in order to optimize the injection of spin-polarized electrons into the channel, nor is it possible to modify them freely in order to optimize the detection of spin-polarized electrons.

A bipolar type of spin transistor is also known as taught by US patent No. 5 962 905. In that patent, the emitter and the base are covered in respective magnetized magnetic layers. Although those two elements are separated by a semiconductor junction, the range over which their potential can be adjusted remains very limited.

An object of the present invention is thus to provide a spin-detection magnetic memory in which the injection and/or detection of spin-polarized electrons is/are significantly improved.

According to the invention, the memory is arranged on a semiconductor junction formed by two adjacent zones, the first and second zones presenting conductivities respectively of a first type and of a second type, the memory comprising first and second connection cells disposed on either side of the junction, with each cell being provided with a magnetization module; in addition, at least one of the cells includes a bias electrode in addition to its magnetization module.

Adding an electrode close to the magnetization module enables the bias of the module to be changed without excessively disturbing the operation of the memory.

Preferably, one of the magnetization modules is adjacent to the semiconductor junction.

In another preferred embodiment, at least one of the magnetization modules includes a buffer layer in contact with the zone in which it is located, a magnetic layer being placed on said buffer layer.

Advantageously, the buffer layer is made of an insulating material, and according to an additional characteristic, its thickness is such as to enable conduction by the tunnel effect between the magnetic layer and the zone in which it is located.

Furthermore, the distance between the two magnetization modules of the memory is less than twice the spin-diffusion length.

In addition, the first layer presents conductivity of p-type.

The present invention appears below in greater detail in the context of the following description of embodiments given by way of illustration with reference to the accompanying figure which is a diagram of the spin detection memory of the invention.

With reference to Figure 1, the magnetic memory is placed on a semiconductor substrate 100.

The substrate 100 has a first zone 101 on which a first connection cell 110 is placed. This first zone 101 presents conductivity of a first type, of p-type in the present example, while the remainder of the substrate which constitutes a second zone 102 presents conductivity of the second type, of n-type in the present example. The boundary between the two zones thus forms a semiconductor junction 103.

In this example, the first connection cell 110 is an injector of spin-polarized electrons. It comprises a first magnetization module formed by a first buffer layer 111 in contact with the first zone 101, and a first magnetic layer 112 placed on said first buffer layer.

The first magnetization module is preferably located in the immediate vicinity of the semiconductor junction 103.

Spin-polarized electrons are injected from the first magnetic layer 112 into the first zone 101.

To inject and detect spin-polarized electrons, it is necessary to have materials that present strong electron-spin polarization: ferromagnetic materials are naturally good candidates. These materials may be insulative, semiconductive, or metallic. For electronic devices such as memories, it is preferable to make use of ferromagnetic metals, since ferromagnetic semiconductors

are materials that have been synthesized only recently and their technology is still not well mastered. In addition, the Curie temperature of those materials is quite low, below 300°K, and they therefore cannot be used at ambient temperature. In contrast, conductive ferromagnetic materials have very high Curie temperatures, much greater than 300°K. Their technology is well mastered and a wide range of ferromagnetic metals (pure metals and alloys) are available with a variety of magnetic properties (coercive fields, magnetic anisotropy, ...).

Electrons can be injected from ferromagnetic metals in various ways, in particular by means of a tunnel junction. Experiments carried out with ferromagnetic metals show that the electrons emitted by such metals through tunnel junctions are strongly spin-polarized.

Thus, the first buffer layer 111 is preferably made of an insulating material such as silicon dioxide or alumina.

It presents a thickness that is sufficiently fine, a fraction of a nanometer to a few nanometers, so that conduction between the first magnetic layer 112 and the first zone 101 is determined by the tunnel effect.

The stack of the first zone 101, the first buffer layer 111, and the first magnetic layer 112 thus constitutes a tunnel junction.

In order to enable this tunnel junction to be forward biased, the first magnetization cell has a bias electrode 113 in resistive contact with the first zone 101. Applying a relatively low voltage, of the order of a few volts, between the first magnetic layer 112 and the first zone 101 suffices to straighten the bands in the semiconductor 101 close to the interface with the first buffer layer 111. It is then certain that electrons can be injected into the conduction band of this semiconductor.

Furthermore, a second connection cell 120 acts as a detector of spin-polarized electrons. Placed on the second zone 102, it comprises a second magnetization module which is preferably formed by a second buffer layer 121 in contact with the second zone 102 and a second magnetic layer 112 placed on said second buffer layer.

It is mentioned above that a tunnel junction significantly increases the efficiency with which polarized electrons are injected. Such a junction also makes it possible in analogous manner to improve the detection of such polarized electrons since the probability of an electron passing into a ferromagnetic material through the junction depends very strongly on the orientation of its spin.

Thus, advantageously, the second buffer layer 121 is made of an insulating material so as to provide a second tunnel junction constituted by the stack comprising the second zone 102, the second buffer layer 121, and the second magnetic layer 122.

In order to improve the spin selectivity of detection, it is preferable to have a second bias electrode 123 in resistive contact with the second zone 102. By way of example, the potential difference between the second magnetic layer 122 and the second bias electrode is of the order of a few volts.

The current injected by the first connection cell 110 for sending to the second connection cell is spin-polarized. In other words, it is constituted by a majority of electrons having a single type of spin, either "up" spin or "down" spin. The extent to which the current is polarized is determined by the band structure of the magnetic material at the interface with the buffer layer. Spin polarization depends on the orientation of the magnetization of the ferromagnetic metal. The injected current I has two components G_+ and G_-,

respectively representing up spin and down spin electron current contributions.

In the second connection cell, the injected current is subdivided into a detection current picked up by the second magnetic layer 122 and a leakage current picked up by the second bias electrode 123. The detection current and the leakage current depend on the relative magnetization of the two magnetization modules.

The detection current when the directions of magnetization of the two modules are parallel and anti-parallel respectively are written i_p and i_{ap}. Similarly, the leakage current when the magnetizations of the two modules are respectively parallel and anti-parallel are written j_p and j_{ap}.

The probabilities that up spin and down spin electrons will be transmitted into the second magnetic layer are characterized by coefficients α_+ and α_-, and the probability of going towards the resistive contact is characterized by a coefficient β which is independent of spin polarization.

In the parallel configuration, the various currents are related to the concentrations n_+ and n_- of electrons respectively having up spin and down spin as follows:

$$I = G_+ + G_-;\ i_p = \alpha_+ n_+ + \alpha_- n_-;\ j_p = \beta(n_+ + n_-)$$

Under steady conditions, and still for a parallel configuration of the relative magnetizations of the injectors and the detectors, we have:

$$G_+ = \alpha_+ n_+ + \beta n_+;\quad G_- = \alpha_- n_- + \beta n_-$$

$$n_+ = \frac{G_+}{\alpha_+ + \beta};\quad n_- = \frac{G_-}{\alpha_- + \beta}$$

$$i_p = \alpha_+ n_+ + \alpha_- n_- = \frac{\alpha_+}{\alpha_+ + \beta} G_+ + \frac{\alpha_-}{\alpha_- + \beta} G_-$$

When the magnetizations of the injector and of the detector are in the anti-parallel configuration, the detected current is modified compared with the parallel configuration:

$$G_- = \alpha_+ n_+ + \beta n_+ ; \quad G_+ = \alpha_- n_- + \beta n_-$$

$$n_- = \frac{G_+}{\alpha_- + \beta} ; \quad n_+ = \frac{G_-}{\alpha_+ + \beta}$$

$$i_{ap} = \alpha_+ n_+ + \alpha_- n_- = \frac{\alpha_+}{\alpha_+ + \beta} G_- + \frac{\alpha_-}{\alpha_- + \beta} G_+$$

If follows that:

$$i_p - i_{ap} = \frac{\alpha_+}{\alpha_+ + \beta} (G_+ - G_-) - \frac{\alpha_-}{\alpha_- + \beta} (G_+ - G_-)$$

$$i_p - i_{ap} = (G_+ - G_-) \left(\frac{\beta(\alpha_- - \alpha_-)}{(\alpha_+ + \beta)(\alpha_- + \beta)} \right)$$

$$i_p - i_{ap} = \frac{\alpha_+}{\alpha_+ + \beta} (G_+ - G_-) + \frac{\alpha_-}{\alpha_- + \beta} (G_+ - G_-)$$

$$i_p - i_{ap} = (G_+ - G_-) \left(\frac{2\alpha_+\alpha_- + \beta(\alpha_+ - \alpha_-)}{(\alpha_+ + \beta)(\alpha_- + \beta)} \right)$$

The following notation is used to quantify the asymmetries of the injected current, of detection, and of the detected current:

$$G_+ = G + \Delta G ; \; G_- = G - \Delta G ;$$

$$\text{whence } G = \frac{(G_+ + G_-)}{2} \text{ and } \Delta G = \frac{(G_+ - G_-)}{2}$$

$$\alpha_+ = \alpha + \Delta\alpha ; \; \alpha_- = \alpha - \Delta\alpha ;$$

$$\text{whence } \alpha = \frac{(\alpha_+ + \alpha_-)}{2} \text{ and } \Delta\alpha = \frac{(\alpha_+ - \alpha_-)}{2}$$

$$i = \frac{(i_p + i_{ap})}{2} \text{ and } \Delta i = \frac{(i_p - i_{ap})}{2}$$

The quantity that characterizes the sensitivity of the detector is $\Delta i/i$, being relative variation of the detection current for two magnetization configurations:

$$\frac{\Delta i}{i} = \frac{\Delta G}{G} \times \frac{2\beta\Delta\alpha}{2\left[\alpha^2 - (\Delta\alpha)^2\right] + 2\beta\alpha} = \frac{\Delta G}{G} \frac{\Delta\alpha}{\alpha} \frac{\beta}{\alpha\left[1 - \left(\frac{\Delta\alpha}{\alpha}\right)^2 + \frac{\beta}{\alpha}\right]}$$

Assuming that $(\Delta\alpha)^2$ is significantly less than α^2, the following relationship is obtained:

$$\frac{\Delta i}{i} = \frac{\Delta G}{G} \times \frac{\Delta\alpha}{\alpha} \times \frac{\beta}{\alpha + \beta}$$

$\Delta G/G$ characterizes the spin polarization of the injected electrons.

$\Delta\alpha/\alpha$ characterizes the transmission anisotropy of the detector.

The ratios $\Delta G/G$ and $\Delta\alpha/\alpha$ are equal to a few tenths, about 0.4 for an alloy of iron and cobalt.

The sensitivity limit thus depends solely on properties of the ferromagnetic structures. It is reached when $\alpha \ll \beta$ or indeed $i \ll j$. The detector thus presents a much weaker current (compared with the injected current), but with maximum sensitivity to spin polarization in the semiconductor. For a detected current representing 10% of the injected current, the sensitivity of the detector will be equal to 90% of the limit sensitivity, as given by the ferromagnetic materials involved.

Using the term "collector" to designate the space that exists between the two magnetization modules, the collector contains a non-negligible concentration of electrons that are not spin-polarized when the injected current is zero. As more and more spin-polarized electrons are injected, these electrons progressively replace the non-polarized electrons. Under steady conditions, a spin-polarization distribution P becomes established in the collector, having the following form:

$$P(x) = P(0)\exp(-x/L_s)$$

where <u>x</u> is the distance between the electron and the semiconductor junction 103, and L_s is the spin-diffusion length.

$$L_s = \sqrt{D\tau_s}$$

where D is the electron diffusion coefficient, and τ_s is the spin-relaxation time.

It is thus preferable for the distance d between the two magnetization modules to be less than the diffusion L_s, even though it is possible for d to be greater than the diffusion length L_s, e.g. twice L_s, to the detriment of detector sensitivity.

In silicon at ambient temperature, the carrier diffusion coefficient and the spin-relaxation time are high enough for electrons to retain their spin over diffusion lengths of several micrometers. Spin-relaxation times for conduction electrons, as measured by electron paramagnetic resonance (EPR) techniques are of the order of 10^{-8} seconds (s). This leads to a value for L_s, i.e. the diffusion length, that is of the order of a few micrometers. For distances d less than L_s, spin relaxation is thus a phenomenon that is negligible and spin becomes a characteristic that is specific to each electron.

The memory of the invention can be fabricated in particular as follows. The method up to the contact portion is a traditional CMOS fabrication method. Before opening contacts or after filling the contact with a metal, an additional step is introduced. Insulation is deposited to a thickness of a few nanometers; this insulation may be silicon dioxide, alumina, or any other known dielectric. Thereafter, the ferromagnetic material is deposited, e.g. an alloy of cobalt and iron. The two constraints imposed on the materials are to have a sharp interface with the dielectric while maintaining high electron polarization at the interface. The thickness of the deposited magnetic material may lie in the range a few tens to a few hundreds of nanometers. Thereafter, a traditional metal such as copper or aluminum is deposited, or indeed any other material that provides good electrical continuity. The circuit is then mechanically and chemically polished so as to leave only

the magnetic material in the injection and detection zones. The method can then return to the traditional path.

The memory is written to or deleted with a magnetic field that serves to reverse the magnetization of the first or the second magnetic layer 112 or 122. Because the current passing through the detector depends on the relative orientation of the magnetizations of the injectors and of the detectors, the magnetic state of the cell is read from the current passing through the detector. As in the prior art, the memory can be written to by passing a current through two insulated metal conductors that cross over the magnetic layer that is to be magnetized.

When a saturation current is conveyed by both conductors, the magnetic field generated at their intersection suffices to cause the magnetization configurations to pass from a parallel state to an anti-parallel state. The saturation current is selected so that the combined magnetic field exceeds the critical magnetic field of the ferromagnetic metal, determined for the most part by its magnetic anisotropy. In addition, if the saturation current is applied to only one of the two conductors, then the magnetic field that is generated is insufficient to change the magnetization. Finally, the arrangement of the conductors is such that the field generated by the saturation current is very localized. This field is below the field needed to change the magnetization of other magnetic elements situated close to the intersection of the two conductors.

The two possible directions of magnetization then define two possible logic states of the memory (commonly written 0 and 1).

Naturally, a plurality of individual or unit memories of the kind described above can be associated to constitute a memory assembly.

The structure of the unit enables it to be integrated with individual components such as transistors, diodes, or capacitors. These components serve to manipulate the read current passing through the various units, and thus make it possible to provide a memory assembly having random access (RAM).

At present, all non-volatile memories (EEPROM, FLASH, FeRAM, MRAM) use fabrication methods that are not standard. Fabrication requires four to five levels of masks to be added, giving an extra cost of about 20%.

In the invention, it becomes possible to fabricate non-volatile memories with a conventional CMOS method, without significantly increasing the various levels of masking. In addition, in comparison with FLASH memories, the memory of the invention operates at low voltage and does not require charge to be pumped. That is a decisive advantage for mobile applications.

The invention is particularly well adapted to so-called system-on-chip (SOC) technology. SOC technology integrates all of the components on a single chip: a microcontroller, SRAM and DRAM memories, dedicated logic, MEMS, chemical sensors, and naturally non-volatile memories. That makes it necessary to have a fabrication method that is as standard as possible.

The embodiment of the invention described above has been selected for its concrete nature. However, it is not possible to list exhaustively all of the embodiments covered by the invention. In particular, any means described may be replaced by equivalent means without going beyond the ambit of the present invention.